# Interaction of trees and snow cover in the treeline ecotone

## Evaluating tree height and snow depth with remote sensing and field measurements at Stillberg in Davos

Bachelor thesis

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Cover: Picture of the research area Stillberg from the opposite hillside with Davos in the background. Taken by the author in march 2016

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# Abstract

The treeline ecotone is considered to be sensitive to changes in climatic conditions. The shift of the treeline will have consequences in different fields such as ecology, hydrology, global carbon cycle and not least in the socio-economic sector, for example in natural hazard protection. Therefore, it is important to understand the dominating processes at the treeline in detail. The elevation and remoteness of the treeline requires new methods to ensure a long-term observation of this unique ecosystem without creating enormous costs and risks. This thesis examined the tree height and snow depth, as well as the influence of the trees on the snow depth in the treeline ecotone at the research area Stillberg in Davos, Switzerland. The data acquisition was carried out with drone-based photogrammetry and field measurements. The results showed that the snow depth underneath the evergreen *Pinus cembra* was 10 times smaller than underneath the deciduous *Larix decidua*. For *Pinus mugo* no statement was possible due to the measurement design. The relation between tree length and snow depth was negative for all three species, though not significant. A comparison of the tree height values assessed manually and estimated from height models, derived from photogrammetry data, showed that the accordance was better for evergreen than for deciduous species. For *Pinus cembra* and *Pinus mugo* it did not matter much whether the data acquisition took place in summer or in winter. For the deciduous *Larix decidua* however, the assessment should be performed during the summer. The height models, derived from the photogrammetry data, on average underestimated the snow depth in forest gaps by 26 cm, however the sample size was very small. This results showed the potential of photogrammetry to easily and quickly assess vegetation height and snow depth in remote areas.

*Keywords*: treeline ecotone, tree height, snow cover, photogrammetry, field measurement.

# Acknowledgements

I would not have been able to write this thesis without the support of various people to whom I would like to say "Thanks a lot":

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Julia Isler, Davos, July 2016

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# Abbreviation

AGNES = Automated Global Navigation Satellite System Network for Switzerland
ALS = airborne laser scan
dGNSS = differential Global Navigation Satellite System
DBH= diameter at breast height
DEM = digital elevation model
DSM = digital surface model
DTM = digital terrain model
m.a.s.l. = meters above sea level
HM = height model. The difference of 2 DSMs or a DSM and a DTM.
NIR = near-infrared
NMAD = normalized median absolute deviation
RGB = visible light band (red - green - blue)
RMSE = root mean squared deviation
SLF = WSL-Institute for Snow and Avalanche Research
UAS = Unmanned aerial system
WSL = Swiss Federal Institute for Forest, Snow and Landscape Research

# 1

# Introduction

## 1.1 Problem description

The treeline ecotone is one of the world's most noticeable changes between vegetation types. The treeline describes the boundary of the highest patches of forest (Grace et al., 2002; Barbeito et al., 2012). The treeline ecosystem is characterised by harsh climatic conditions, a short growing season and a continuous snow cover over several month (Wieser, 2012). The soils are usually rich in humus and skeletal material since the soil formation processes occur slowly. Processes such as mineralisation and decomposition are inhibited by high soil water availability and low soil temperatures which leads to a low nutrient availability for plants (Wieser and Tausz, 2007). However, it is unclear which environmental variables determine the position of the treeline. The limitation of growth by elevation, temperature, resource usage, a combination of abiotic and biotic factors are hypotheses which received attention (Grace et al., 2002; Wieser, 2012; Barbeito et al., 2012). As many processes are limited by the cold temperatures, this climatically determined ecotone is prone to changes in temperature regime and therefore to climate change. This will result in various implications in different fields such as biodiversity, global carbon cycle, ecology and socio-economic sector such as hazard protection (Subedi, 2009; Grace et al., 2002). Grace et al. (2002) showed in their review, that the migration rates which were estimated from simple assumptions did not agree well with the observed migration rates. Therefore, it is important to understand the processes at the treeline ecotone in detail to be able to predict the impact of the climate change on the treeline ecotone.

Hence, this thesis will focus on the interaction of trees and snow cover at the treeline ecotone in the research area Stillberg in Davos, Switzerland. Barbeito et al. (2012) showed, that the snowmelt date was the most important environmental factor for the tree mortality of the tree species present at Stillberg (Swiss stone pine (*Pinus cembra*), mountain pine (*Pinus mugo*) and European larch (*Larix decidua*)). The duration of the snow cover is primarily determined by the amount of snow. This in turn depends on the snow deposition which is influenced by various factors including, amongst other things, micro-topography, wind direction, stand characteristics and radiation (Holtmeier, 2009). Various studies showed, that the snow depth distribution (independent of the mean snow depth) is similar in different winters due to the main wind direction (Gubler and Rychetnik, 1991; Rasmus et al., 2011; Schirmer et al., 2011; Bühler et al., 2015b). Holtmeier (2009) suggested to use the mean snow depth to distinguish the climate character of an area. Because of the analogue snow depth distribution every year, the vegetation at a specific location is influenced similarly each winter. The snow depth influences the vegetation distribution, growth, regeneration and mortality and in central Europe it is expected to gain importance (Hlásny et al., 2011). Rasmus et al. (2011) point out that it is important to understand the snow-vegetation interaction associated with uneven snow cover. Various processes such as gliding and creeping, damage or protection caused by the snow cover affect the trees (Frey, 1977; Salm, 1978; Nykänen et al. 1997; Kellomäki and Peltola, 1999; Zhu et al., 2006).

The vegetation on its part affects the snow depth as well. This has at least one major socio-economical effect: Avalanche protection due to the stabilisation of the snow cover (Meyer-Grass and Schneebeli, 1992; Margreth, 2004; Schneebeli and Bebi, 2004). The stabilisation of the snow cover is based on the modification of the mechanical properties of the snow. On one hand, the stems directly support the snow pack. On the other hand the formation of continuous, unstable snow layers which favour slab avalanche formation is reduced by processes such as interception, modification of the radiation and reduction of near-surface wind speed (Schneebeli and Bebi, 2004). The interception depends on the conformation of the stand, the altitude, the weather and the climatological conditions (Frey, 1977; Nykänen et al., 1997). It increases with a larger leaf area index and canopy cover, which in winter results in a larger interception for evergreen species compared to deciduous species (Hedstrom and Pomeroy, 1998). Frey (1977) indicates, that the snow interception in many cases is 10 - 30% of the snow fall for coniferous species, while it is only 5 - 15% for deciduous species. The intercepted snow either falls to the ground later on, sublimates directly or is redistributed by wind. Gubler and Rychetnik (1991) showed, that the sublimation of intercepted snow occurs faster compared to the snow on the ground, because of its higher surface:volume-ratio. Further, the tree alters the regime of the solar radiation by shadowing and long-wave emission from the canopy (Schneebeli and Bebi, 2004; Margreth, 2004; López-Moreno and Stähli, 2008). The influence of the near-surface wind speed is in general considered to be small in dense forest stands. However it is unclear how dense the stand has to be and what the minimal size of a clearing is in which snow distribution by wind gets relevant (Gubler and Rychetnik, 1991; Schneebeli and Bebi, 2004; Margreth, 2004; Rasmus et al., 2011). Despite which of these mechanisms is dominating, it leads to a uneven snow cover structure underneath the crown compared to the open field (Salm, 1978; Margreth, 2004; Schneebeli and Bebi, 2004). The snow depth underneath a tree depends on the canopy density, distance to the trunk, diameter and height (López-Moreno and Latron, 2008; Revuelto et al. 2014).

Due to its elevation, the treeline ecotone often is not easily accessible or in winter even not accessible due to avalanche danger. Treeline research is therefore time intensive and expensive. Newly available remote sensing techniques offer new possibilities to map vegetation heights, snow depth and ground surface elevations (Deems et al., 2013). Airborne laser scanning (ALS) from helicopters or aeroplanes enables a safe and accurate snow depth mapping over a large area. However, it is expensive and restricted to good weather conditions. This is also true for digital photogrammetry, indeed it is much more economical than the ALS data acquisition (data acquisition and processing)(Bühler et al., 2015b). The use of unmanned aerial systems (UAS) for digital photogrammetry results in cheaper, easier data acquisition with high spatial resolution, resulting in accurate orthophotos and digital surface models (DSMs) (Bühler et al., 2015a). However, it is unclear if the snow depth mapping with UAS-based photogrammetry is suitable for forested areas (Bühler et al., 2015b).

## 1.2 Aim of the thesis, research question and hypothesis

This thesis aimed at showing whether the snow depth underneath a tree depends on the tree species or not. Furthermore, it examined the influence of the tree length on the snow depth underneath the tree. Moreover, hand-measured data of tree height and snow depth were compared to the corresponding heights, respectively depths estimated from height models (HMs). The HMs resulted from the difference of digital elevation models (DEMs). The DEMs derived from photogrammetry data- either UAS- or ALS-based. The hand-measured data will be referred to as "manually assessed" and the values, estimated from HMs, are referred to as "estimated". The following research questions have been addressed:
**Question 1**: Is the snow depth underneath a tree influenced by the tree species?

> ***Hypothesis 1***: The snow depth is expected to be lower underneath evergreen species (*Pinus cembra, Pinus mugo*) than underneath deciduous species (*Larix decidua*).

**Question 2**: Does the tree length influence the snow depth underneath its crown?

> ***Hypothesis 2***: The snow depth is expected to be lower underneath larger trees.

**Question 3**: How well do the values for tree height gained from photogrammetry data correspond with the manually assessed values?

> ***Hypothesis 3.1***: The manually assessed tree height is not expected to vary significantly from the estimated tree height, which is gained from height models, derived from photogrammetry data.
>
> ***Hypothesis 3.2***: The estimated tree height, which is gained from height models, derived from photogrammetry data, is expected to agree better with the manually assessed values for evergreen species (*Pinus cembra, Pinus mugo*) than for deciduous species (*Larix decidua*).

**Question 4**: How well do the values for snow depth, gained from height models, derived from photogrammetry data correspond with the manually assessed values?

> ***Hypothesis 4***: The manually assessed snow depth is not expected to be significantly different from the estimated snow depth, which is gained from height models, derived from photogrammetry data.

## 1.3 Study area

The research area "Stillberg" (46°46’ N, 9°52’ E (WGS84)) is located on the left hand side of the Dischma valley in Davos, Switzerland (figure 1.1).

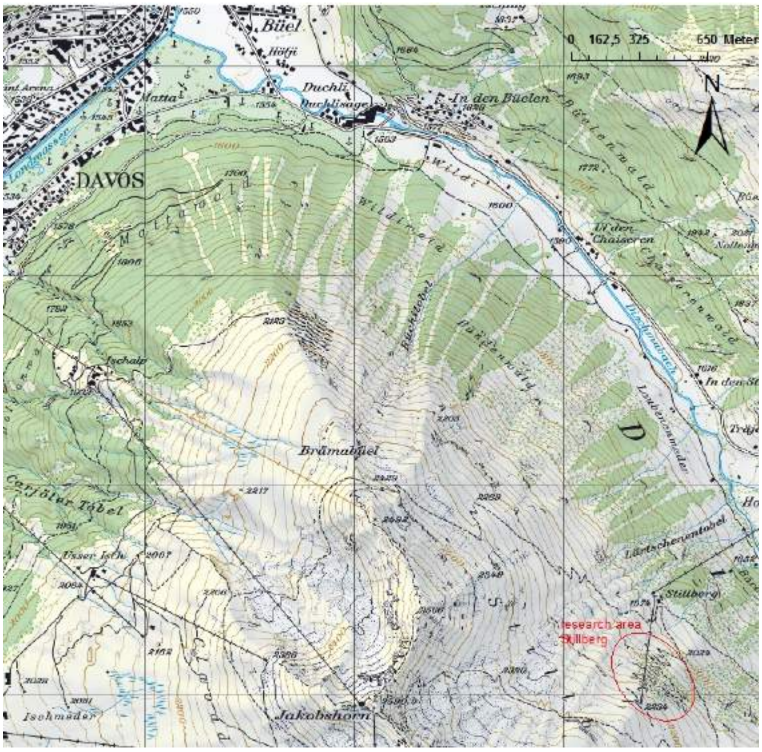


**Figure 1.1: The research area Stillberg**: The geographical position of Stillberg, with respect to Davos

The research site was established in the 1950s as a joint research project of the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) Birmensdorf and WSL-Institute for Snow and Avalanche Research (SLF) Davos. The 10 ha large area with north-east exposure is positioned in the avalanche starting zone. The elevation ranges from 2000 m up to 2230 m.a.s.l. (Senn and Schönenberger, 2001) and the timberline is situated at about 2100 m.a.s.l (Barbeito et al., 2012). Following the elevation, the inclination of the slope changes, ranging from 60 up to 100%. The climate is considered to be moderate continental with relatively warm summers (average temperature in July = 9.4℃) and relatively cold winters (average temperature in January = -5.8℃). The average annual precipitation is 1050 mm, while the average snow depth amounts to 1.46 m, although it varies between 60 cm and 420 cm, depending on the topography and wind directions. (Senn and Schönenberger, 2001). The average annual temperature is 2.1℃ (1975-2015 mean)(SLF, unpublished data). This temperature range is known to be typical for the distribution area of a Larch-Swiss stone pine-forest (*Larici-Pinetum cembrae* -forest, Nr. 59 according to Ellenberg and Klötzli, 1972).

The area consists of different terrain types such as ridge, north or east facing slope or gulley and is further divided into 5 avalanche chambers (figure 1.2 and 1.3).

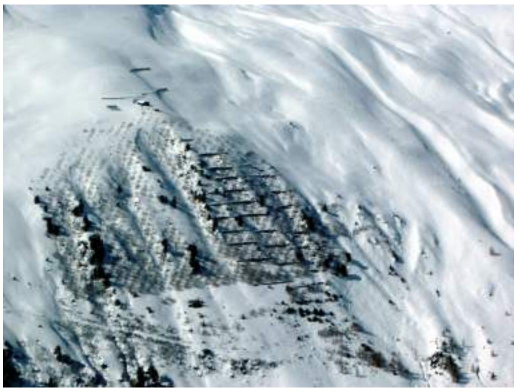


**Figure 1.2: Stillberg**: The research area from the opposite hillside, March 20th 2016

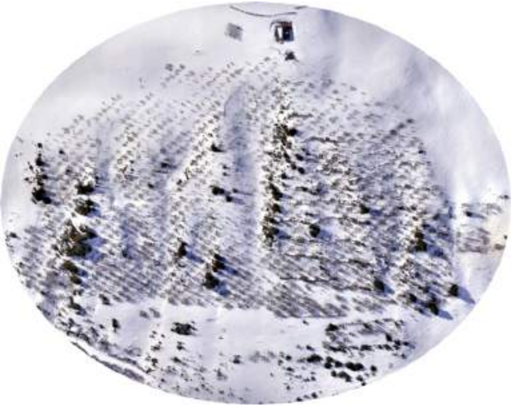


**Figure 1.3: Orthophoto**: Top view of the research area, April 11th 2016

This diverse topography leads to a small scale variation in soil characteristics and vegetation composition. Particularly, it results in differently developed podsol soils, and a vegetation composed of dwarf-shrub communities and reed grass lawns (Senn and Schönenberger, 2001).

### 1.3.1 Experimental set-up and plantation

The long-term afforestation research area is 5 ha large and is separated into unit areas of 3.5 m x 3.5 m. The plantation was performed in 1975 and the planting pattern followed the consequent rules: Each unit area contains trees of one of the following three species: European larch (*Larix decidua* Mill.), Swiss stone pine (*Pinus cembra* L.) and the upright form of the mountain pine (*Pinus mugo* Turra). The design of the total 4025 plots creates a pattern in which the three species are altered regularly (figure 1.4). Within each unit area, 25 seedlings of the accurate species were planted with a distance of 0.7 m to each other (figure 1.5)(Barbeito et al., 2012). Each tree has its own Tree_ID which consists of the number of the unit area, followed by the number of the tree within the unit area, separated by a underscore. For example, the Tree_ID 1339_23 belongs to the 23rd tree within the unit area 1339. They have been monitored (partly intensive, partly random) ever since the plantation was carried out and a large data set has been acquired, containing information such as tree length in different ages, perpendicular height, diameter, tree trunk characteristics and further more. In addition to the plantation, 400 snow stakes were installed and in one third of the research area avalanche barriers were mounted. They were installed dispersed and continuously in two different sub-areas (figure 1.4).

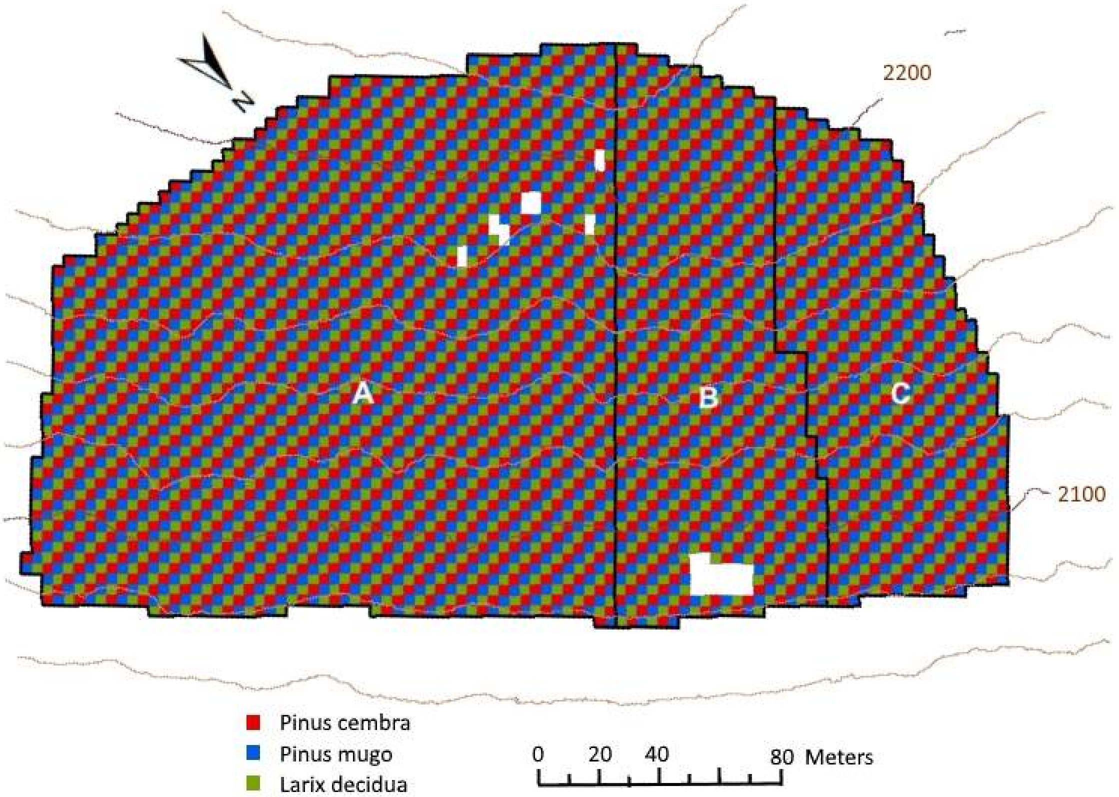


**Figure 1.4: Arrangement of the unit areas and avalanche barriers**: The pattern of the unit areas containing *Pinus cembra* (red), *Pinus mugo* (blue) and *Larix decidua* (green) and the areas with no avalanche barriers (A), respectively continuously (B) or dispersed installed (C) avalanche barriers

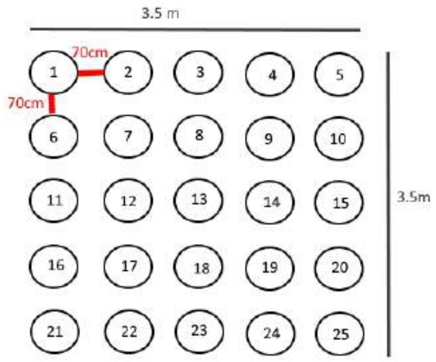


**Figure 1.5: Planting pattern** Arrangement of the trees within a unit area

# 2

# Methods

## 2.1 Data basis

The SLF Davos kindly provided a comprehensive data set containing various variables assessed at Stillberg over a time period of 40 years. For this thesis the data of the following variables, assessed in the complete inventory assessed in summer 2015, has been used:

- Tree length
- Survival
- Tree height

The first two variables have been periodically assessed for all three tree species. The tree height was assessed for the first time in summer 2015. Furthermore, the SLF and the WSL provided several DEMs (DSMs and DTMs (digital terrain model)) of the research area. A DSM represents the surface including vegetation, as well as buildings and infrastructure, whereas the DTM is a model of the terrain only. The characteristics of the models can be extracted from the table 2.1.

**Table 2.1:** Characteristics of the DEMs used in this thesis

| name | type | resolution | date of acquisition | used for: |
|---|---|---|---|---|
| DSM_UAV_1 | raster | 5 cm | 11-04-2016 | all winter HM's (model 1-3) |
| DSM_UAV_2 | raster | 5 cm | 12-08-2015 | winter HM (model 1), summer HM |
| DTM_UAV | raster | 5 cm | 12-08-2015 | winter HM (model 3) |
| DTM_ALS | raster | 20 cm | 05-08-2015 | winter HM (model 1 and 3), summer HM |

## 2.2 Field investigation

The field investigation was planned with the support of Peter Bebi (SLF) and took place from the 11th until the 13th of April 2016. On the first day the winter drone acquisition was carried out by Yves Bühler (SLF) and Andreas Stoffel (SLF). During the following two days the tree heights and snow depths were measured by a team of four people, composed of SLF-interns and the author.

### 2.2.1 Variable definition

The variables used in this thesis are defined in this subsection. The methods, how the single variables were assessed are found in the subsections 2.2.3 and 2.2.4.

#### Tree length

The tree length is the distance from the ground surface up to the apical tip of the previous year, measured along the trunk. If the measurements take place during a vegetation period, the length is only measured up to the apical tip of the previous year, since the sprout of the current year still resides in the growing process and has not reached its full expansion yet. Therefore, the tree length measured in summer 2015 reached from the ground surface up to the apical tip of the sprout from 2014.

#### Tree height

The tree height describes the vertical distance from the apical tree tip perpendicular to the ground surface. The tree heights used in this thesis were measured in summer 2015 and in winter 2016. The data of summer 2015 followed the above mentioned rule of excluding the annual shoot from the measurement and were therefore quantified up to the apical tip of 2014. Meanwhile, the tree height, measured in winter 2016, includes the accrescence of 2015.

#### Snow depth

The snow depth is defined as the vertical distance from the snow cover surface to the ground surface at a defined spot.

### 2.2.2 UAS flight mission

Before the UAS flight mission took place, 15 ground control points were established by spraying crosses on the snow surface, using a blue spray can. A differential Global Navigation Satellite System (dGNSS) point was measured with the Trimble GeoXH 6000 dGNSS device in the middle of each cross to be able to orientate the aerial images later on. They were measured with real-time correction with reference to the AGNES (Automated GNSS Network for Switzerland) station DAV2 (http://www.swipos.ch/Map/SensorMap.aspx). The expected accuracy is better than 10 cm.

An octocopter (AscTec Falcon 8, total weight 2.3 kg, incl. the camera) with a Sony NEX-7 camera with a small optical lens (Sony NEX 20 mm F/2.8, 81 g) was used for the data acquisition (figure 2.1). The built-in short pass filter of the camera was removed to enable sensitivity to near-infrared (NIR) spectrum, allowing the use of different filters for visible (RGB) and NIR bands. For data acquisition in winter 2016 a RGB filter was used. The flight plan was previously created using the AscTec Navigator software on a tablet computer, which was connected to the ground control station at the test site. The UAS moved automatically from one way point to the next with exception of the starting and landing phase, which had to be performed manually. A total of 490 pictures, were taken, with an overlap of 70% along-track and cross-track. An area of 182000 m$^2$ was covered, resulting in a dense point cloud with approximately 210 million points. For detailed information about mapping snow depth in alpine terrain with UASs the reader is referred to Bühler et al. (2016).

**Figure 2.1: The UAS**: The AscTec Falcon 8 with the Sony NEX-7 camera (©Yves Bühler)

### 2.2.3 Trees

The sampling design was conducted according to the following criteria:

- The tree is situated in the part of the research area, which contains avalanche barriers (figure 1.4)
- Approximately equal distribution of the total number of trees among the three tree species (*Pinus cembra*, *Pinus mugo*, *Larix decidua*).

The location of the individual trees and their distribution is visualized in figure 2.3. The tree height was measured for each selected tree. A avalanche probe with 5 cm labelling was used to reach through the snow cover to the ground. A folding yard stick was used to determine the height of the tree above the snow cover (figure 2.2). If the yard stick was not stable enough, a second avalanche probe was used to determine the height. The wintergreen species have been measured without the needles.

### 2.2.4 Snow cover

The snow depth was measured with an avalanche probe with 5 cm labelling. Two different snow depth measurements were taken. On one hand it was measured perpendicularly underneath the tree tip at the same time as the tree height was

**Figure 2.2: Field investigation**: Example of measuring the tree height and snow depth, perpendicularly underneath the tree tip

assessed (figure 2.3) ("snow depth perpendicular underneath the tree tip"). One the other hand, five snow depth measurements were taken on fifteen additional spots in forest gaps. Four of them formed a square with approximately 1 m side length, while the fifth measurement was taken in the middle of the square (figure 2.4). The centre point was additionally recorded with a Trimble GeoXH 6000 dGNSS device. The mean of the five snow depth values was used in the analysis ("snow depth in forest gaps").

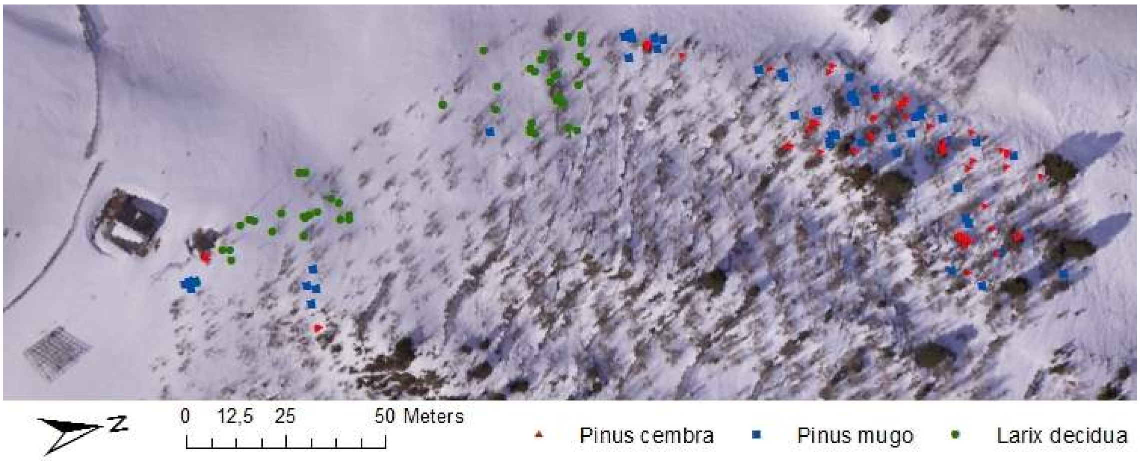


**Figure 2.3: Assessed trees**: A picture containing all trees for which the tree height and the snow depth perpendicular underneath the tree tip were assessed - *Pinus cembra* (red), *Pinus mugo* (blue) and *Larix decidua* (green).

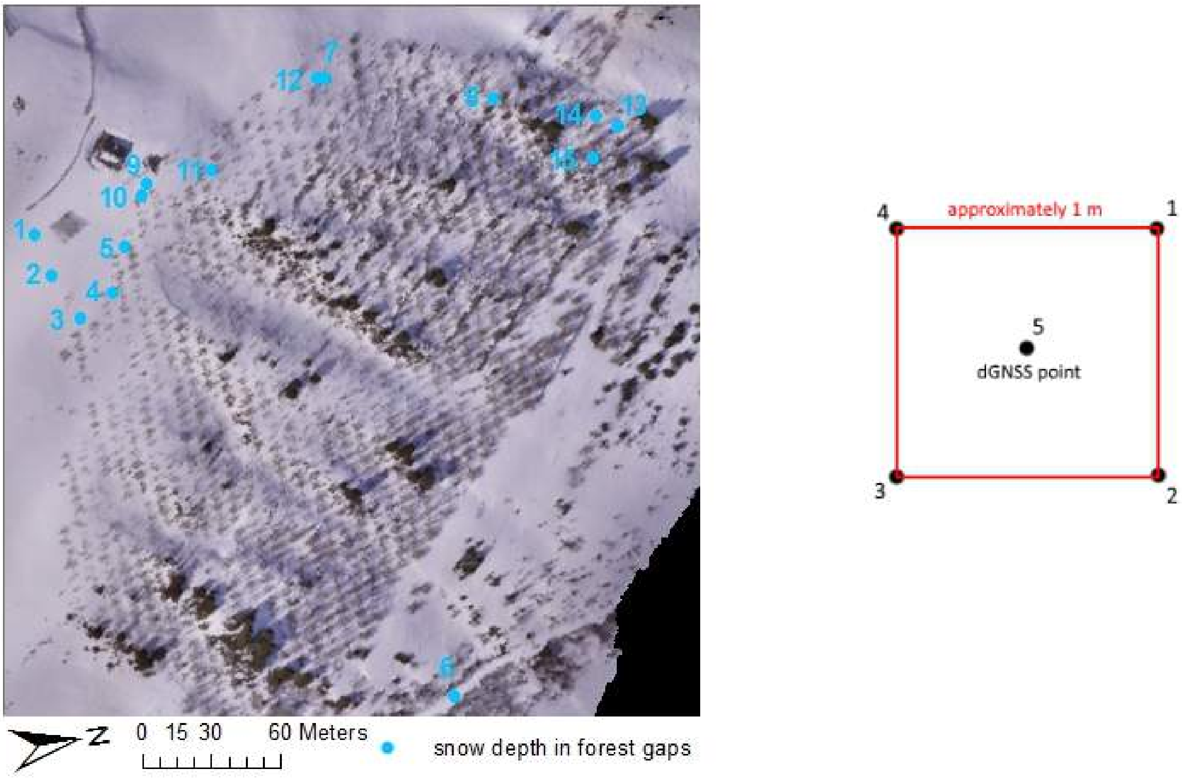


**Figure 2.4: Snow depth in forest gaps**: Locations where the snow depth in forest gaps was assessed, as well as the design of the measurement.

## 2.3 Data processing and analysis

The data was processed and analysed by using ArcMap 10.3 (ESRI, 2015) and the statistic software R and R Studio Version 0.98.1102 (R Core Team, 2014). The only exception is the data processing of aerial images, described in subsection 2.3.2.

### 2.3.1 Field data

The values for the variables measured manually in the field were transferred into an excel-file, which was save in the .csv-format (comma-separated value) to enable the import in R Studio. Missing values were defined as NA.

### 2.3.2 UAS-based photogrammetry - data processing

The aerial images were used to create a georeferenced DSM and the orthophoto (figure 1.3). They were processed with Agisoft PhotoScan Prov v1.1.6, using dense point cloud generation with the default parameters. This resulted in a DSM with a resolution of 5 cm and an orthophoto with a resolution of 2 cm. For detailed information about UAS and data processing, the reader is referred to Bühler et al. (2016). To be able to extract information such as tree height it is necessary to classify the ground points correctly. The height of the dGNSS ground control points were compared with the median of the heights of the classified ground points to be able to show the accuracy of the ground points. The height accuracy of the ground control points was better than 10 cm. The height accuracy of the photogrammetry ground points depends on the method (UAS or ALS) and the vegetation. It is known to be better for areas with grasses and Vaccinieae than for areas covered with rhododendron (Marty, 2016). This leads to a height accuracy of the resulting HM of +/- 10 cm.

### 2.3.3 DSM derived from UAS-based photogrammetry - estimated tree height and snow depth

In a first step the HMs were calculated. Different DEMs were subtracted from one another using the "Raster calculator"-Tool of ArcGIS (table 2.1). The HMs illustrate the height of vegetation or infrastructure above the bare ground surface. If the two models did not have the same resolution, the one with the higher resolution was aggregated up to the same resolution level as the other model by using the "Aggregate"-Tool of ArcGIS with the maximum method. Table 2.2 gives an overview of the calculated models.

**Table 2.2:** Characteristics of the DSMs and DTMs used to produce the HMs (model x= Model A minus Model B)

| name | Model A | Model B | resolution | used for: |
|---|---|---|---|---|
| model 1 | DSM_UAV_1 | DTM_ALS | 20 cm | tree heights (winter) and snow depth |
| model 2 | DSM_UAV_1 | DSM_UAV_2 | 5 cm | snow depth |
| model 3 | DSM_UAV_1 | DTM_UAV | 5 cm | snow depth |
| model 4 | DSM_UAV_2 | DTM_ALS | 20 cm | tree heights (summer) |

A shape-file with the position of the tree tip of each investigated tree was created manually (figure 2.3). The position of the tree tip was determined by a visual comparison of the orthophoto (figure 1.3) and the corresponding HM. This was done for the winter data (DSM and orthophoto of 11-04-2016) and the summer data (DSM and orthophoto of 12-08-2015). Furthermore, the dGNSS points of the measurement locations for snow depth in forest gaps were drawn in a layer file. With the ArcGIS-tool "Extract values to points" the tree height information for each tree was gained by extracting it from the corresponding raster cell in the HMs. The same procedure was followed with the layer of the dGNSS points to gain the snow depth information. These values will be referred to as "estimated", while the tree height, respectively snow depth, measured in the field, will be described as "manually assessed". The attribute tables of these extracted points were exported into .csv-files and imported into R Studio.

### 2.3.4 Statistical analysis

The total data set contained 101 observed trees and the following eight variables:

- Tree_ID_15
- tree species number
- tree height in summer 2015 and winter 2016
- tree length in summer 2015
- estimated tree height in summer 2015 and winter 2016
- snow depth perpendicular underneath the tree trip.

It was divided into 3 smaller data sets containing only the information for one tree species. The data set of *Pinus cembra* and *Pinus mugo* each contained 32 observations, while the data set of *Larix decidua* was composed of 37 observations. The data set of snow depth in forest gaps contained 15 observations. The groups were tested with a "Shapiro-Wilcoxon-Test" to determine, whether they were normally distributed or not. To assess the relationship between two variables the Pearson's r has been calculated. The level of significance for all tests was 5%.

For the comparison of the tree height and snow depths assessed with two methods the two following statistical parameter were calculated (Höhle and Höhle, 2009):

- RMSE = root mean squared deviation. The RMSE is not robust against outliers. It describes the mean of the differences between the methods. Taking in account, that the difference can either be positive or negative:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\Delta h_i^2}$$

- NMAD = normalized median absolute deviation. It is a robust estimator for the standard deviation.

$$NMAD = 1.4826 * median_j(|\Delta h_j - median(\Delta h)|)$$

whereas n = number of observations, h = difference between the methods (manual - estimated)

Furthermore the error was calculated - assuming the manually assessed value to be correct.

Additionally, graphical analysis was carried out to support the statistical analysis. The following plot types were used:

- Box plots - to show the median, the quantiles, as well as the variation of the data.
- Scatter plots - to graphically assess the dependency of two variables and they were supplemented by the corresponding correlation values (Pearson's r).
- Bar plots were used to show the differences between two measurement methods.

# 3

# Results

## 3.1 Influence of the tree species on the snow depth in its crown area

The snow depth perpendicular underneath the tree tip was different for the three investigated species (figure 3.1). It was largest underneath *Larix decidua* (median = 100 cm). A similar variance as for the data of *Larix decidua* was found for *Pinus mugo*, the snow depth however was 1.6 times smaller. The lowest snow depth, also with least variance in the data set, was found underneath *Pinus cembra* (median = 10 cm).

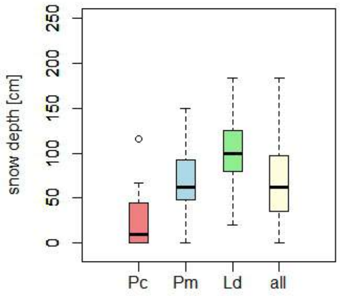
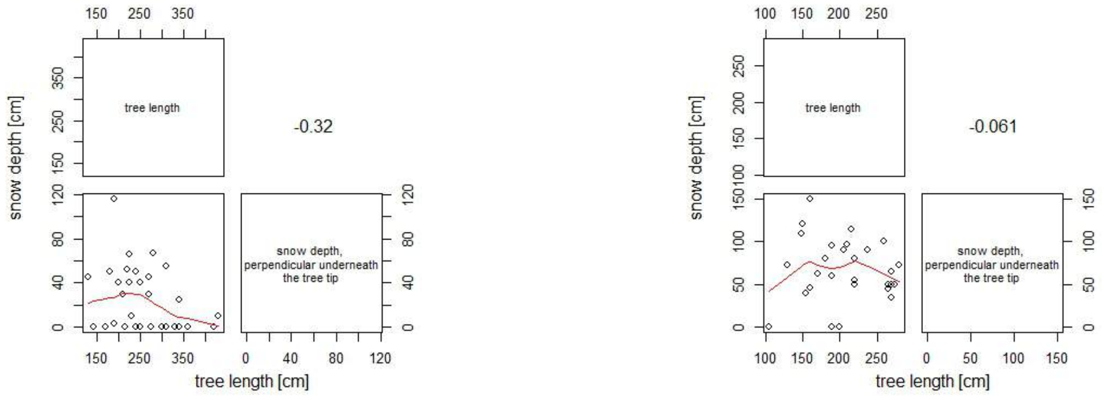


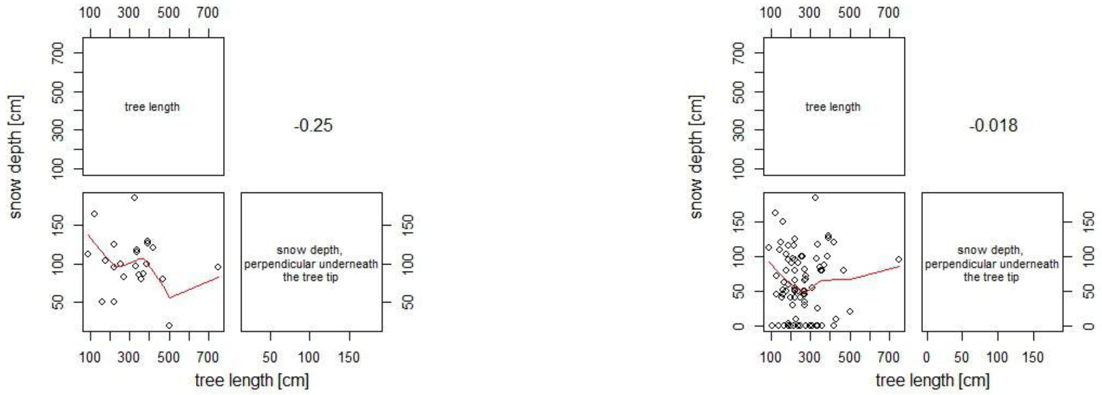
**Figure 3.1: Snow depth perpendicular underneath the tree tips**: This graph shows the snow depth, perpendicular underneath each tree tip, for each species (Pc = *Pinus cembra* (red), Pm = *Pinus mugo* (blue), Ld = *Larix decidua* (green)) separately and all assessed trees together(all,yellow).

## 3.2 Influence of the tree length on the snow depth in its crown area

With increasing tree length, the snow depth underneath the tree tip decreased. However, this relation was weak (figure 3.2). The Pearson's r is distributed in the upper panel of the graph. The correlation of the two variables was for all species negative. The strongest correlation was found for *Pinus cembra*, although it was still not significant (table 3.1). *Pinus mugo* showed the weakest correlation between these two variables.



**(a)** *Pinus cembra* **(b)** *Pinus mugo*



**(c)** *Larix decidua* **(d)** *all species*

**Figure 3.2: Relation between tree length and snow depth**: This graph shows the relation between the tree length, measured in summer 2015, and the snow depth perpendicular underneath the tree tip, measured in winter 2016 for all the species separately (a-c) and all assessed trees together (d). Additionally, a regression line was added in the lower panel, while the Pearson's r appears in the upper panel.

**Table 3.1:** P-values of the Pearson's correlation of the tree length and the snow depth perpendicular underneath the tree tip

| Tree species | p-value of the tree length and the snow depth perpendicular underneath the tree tip |
|---|---|
| *all assessed trees* | 0.8736 |
| *Pinus cembra* | 0.0756 |
| *Pinus mugo* | 0.7547 |
| *Larix decidua* | 0.2451 |

## 3.3 Tree height - manually assessed vs estimated

### 3.3.1 Comparison of the two methods in winter 2016

In winter, the manually assessed tree heights were larger, than the estimated ones (figure 3.3). This pattern was true for all three tree species, but the difference between the methods varied for each species (table 3.2). The tree height values of the two methods corresponded best for *Pinus cembra* (RMSE = 65.9 cm), compared to *Pinus mugo* (RMSE = 87 cm) and *Larix decidua* (RMSE = 266.3 cm). The NMAD values can be extracted from table 3.3. The characteristics of the data set (median, variance, outliers) for *Pinus cembra* was similar in both seasons. The tree height values from the two different methods agreed well for *Pinus mugo*, however the variance of the manually measured data was larger than for the estimated data. The largest difference between the two methods has been observed for *Larix decidua*.

**Table 3.2:** Median of the tree heights in summer 2015 and winter 2016 - assessed manually or estimated from height models, derived from photogrammetry data

| Season | Tree species | Median of the manually assessed tree heights [cm] | Median of the estimated tree heights [cm] |
|---|---|---|---|
| summer | *all assessed trees* | 250 | 226 |
| summer | *Pinus cembra* | 250 | 256 |
| summer | *Pinus mugo* | 220 | 173 |
| summer | *Larix decidua* | 340 | 286 |
| winter | *all assessed trees* | 275 | 143 |
| winter | *Pinus cembra* | 254 | 218 |
| winter | *Pinus mugo* | 220 | 149 |
| winter | *Larix decidua* | 369 | 113 |

**Table 3.3:** NMAD and RMSE of the difference between the tree heights in summer 2015 and winter 2016 - assessed manually or estimated from height models, derived from photogrammetry data

| Season | Tree species | RMSE [cm] | NMAD [cm] |
|---|---|---|---|
| summer | *all assessed trees* | 85.9 | 51.5 |
| summer | *Pinus cembra* | 72.9 | 34.7 |
| summer | *Pinus mugo* | 72.7 | 60.0 |
| summer | *Larix decidua* | 115.4 | 69.4 |
| winter | *all assessed trees* | 173.1 | 100.8 |
| winter | *Pinus cembra* | 65.9 | 43.3 |
| winter | *Pinus mugo* | 87.0 | 58.5 |
| winter | *Larix decidua* | 266.3 | 115.2 |

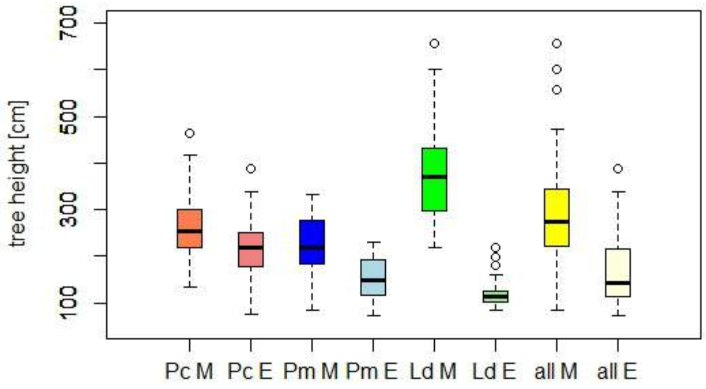


**Figure 3.3: Tree height values in winter 2016 - assessed manually or estimated from height models, derived from photogrammetry data**: This graph shows the tree heights values of the two methods for each species (Pc = *Pinus cembra* (red), Pm = *Pinus mugo* (blue), Ld = *Larix decidua* (green)) separately and all assessed trees together (all, (yellow)). The box plots in darker color show the manually assessed perpendicular tree height values (M), while the ones in brighter color show the estimated tree heights (E).

### 3.3.2 Comparison of the two methods in summer 2015

The comparison of the two methods in summer showed a similar pattern as in winter (table 3.2), however the differences between the methods changed (figure 3.4). The RMSE was similar for *Pinus cembra* (72.9 cm) and *Pinus mugo* (72.7 cm), whereas it was larger for *Larix decidua*( 115.4 cm). The accordance of the tree height values was still best for *Pinus cembra*, however the values of the estimated tree height was slightly larger than the manually assessed ones. The difference between the two methods decreased for *Pinus mugo* compared to the winter assessment, although still showing the same pattern. For *Larix decidua* the two values concurred much better in summer than in winter, yet showing the same pattern - larger manually assessed tree height than estimated.

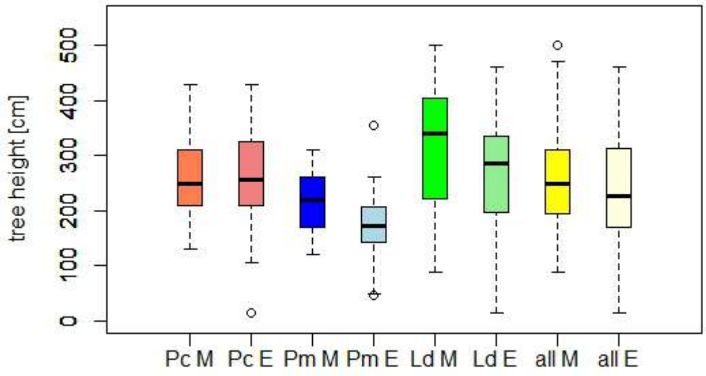


**Figure 3.4: Tree height values in summer 2015 - assessed manually or estimated from height models, derived from photogrammetry data**: This graph shows the tree heights values of two methods for each species (Pc = *Pinus cembra* (red), Pm = *Pinus mugo* (blue), Ld = *Larix decidua* (green)) separately and all assessed trees together (all, yellow). The box plots in darker color show the manually assessed perpendicular tree height values (M), while the ones in brighter color show the estimated tree heights (E).

### 3.3.3 Comparison of the differences between the methods in summer 2015 and winter 2016

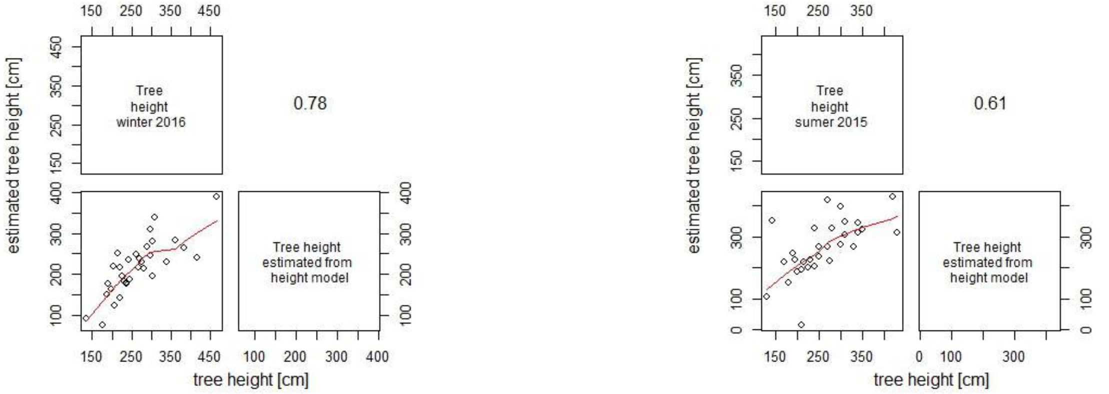
The correlation of the two methods assessed in summer 2015 and in winter 2016 is illustrated in figure 3.5, in which the Pearson's r are shown in the upper panels. The p-values of the correlations can be found in table 3.4. While the perpendicular tree height and the estimated tree height correlated better in winter, than in summer for *Pinus cembra*(winter = 0.79, summer = 0.65), it was the other way around for *Pinus mugo* (winter = 0.43, summer = 0.55). However, the largest difference was observed for *Larix decidua*, where the correlation in summer was more than three times stronger than the one in winter (winter = 0.23, summer = 0.83). In winter the correlation was best for *Pinus cembra*, continued by a less strong correlation for *Pinus mugo*, whereas the correlation for *Larix decidua* was weak. In summer the order changes: the values for *Larix decidua* correlated best, followed by *Pinus cembra* and *Pinus mugo*.

**Table 3.4:** P-values of the Pearson's correlation of perpendicular tree height and the tree height estimated from height models, derived from photogrammetry data (in summer 2015 or winter 2016)

| Tree species | p-value of the correlation of the perpendicular and estimated tree height in summer | p-value of the correlation of the perpendicular and estimated tree height in winter |
|---|---|---|
| *Pinus cembra* | 0.0003 | $1.2*10^{-7}$ |
| *Pinus mugo* | 0.0073 | 0.0127 |
| *Larix decidua* | $4.8*10^{-7}$ | 0.17 |

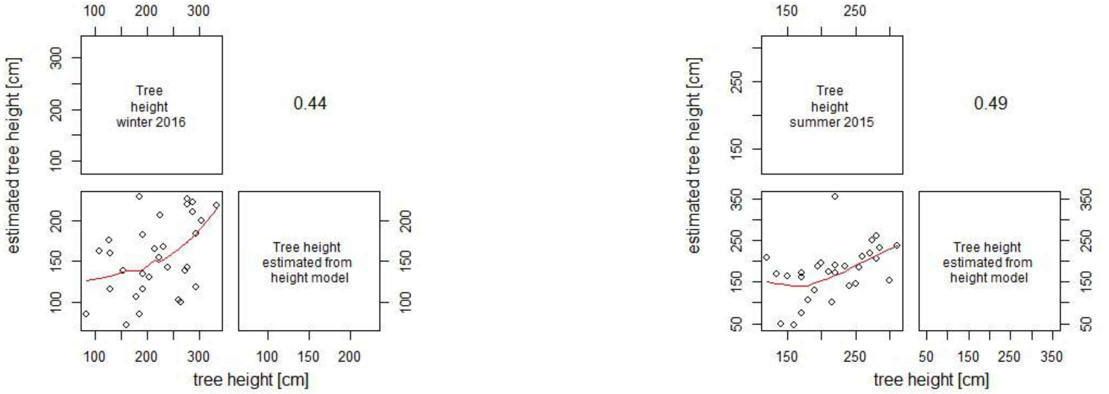
The difference between the methods was smaller in the summer acquisition, than in the winter acquisition for all three tree species (figure 3.6). However, there were more outliers in summer than in winter. The difference between the methods between the seasons was smallest for the two evergreen species (*Pinus cembra*: RMSE summer = 72.9 cm, winter = 65.9 cm; *Pinus mugo*: RMSE summer = 72.7 cm, winter = 87 cm), whereas it was largest for the deciduous *Larix decidua* (RMSE summer = 115.4 cm, winter = 266.3 cm).

The distribution of the measurement error showed that the tree height was always underestimated by the values gained from the HM, derived from photogrammetry (figure 3.7). The only exception was *Pinus cembra* in the summer acquisition (mean error= - 4 cm). Beside this exception, the tree height was underestimated by roughly 50 cm for evergreen species (*Pinus cembra* winter: mean error = 48 cm; *Pinus mugo* summer: mean error = 42 cm, winter = 64 cm). The error for the deciduous *Larix decidua* is smaller in summer (mean error = 82 cm) than in winter (mean error = 248 cm).



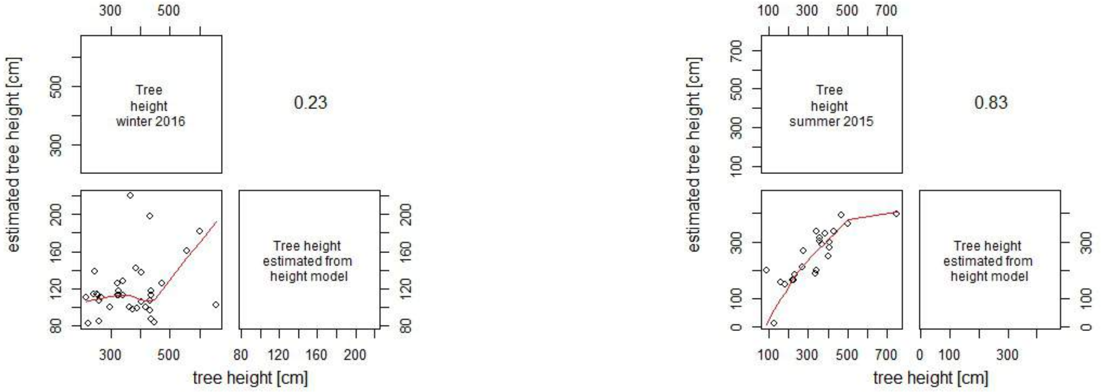
**(a)** *Pinus cembra*, winter 2016

**(b)** *Pinus cembra*, summer 2015



**(c)** *Pinus mugo*, winter 2016

**(d)** *Pinus mugo*, summer 2015



**(e)** *Larix decidua*, winter 2016

**(f)** *Larix decidua*, summer 2015

**Figure 3.5: Relation between the tree height in summer 2015 and winter 2016 - assessed manually or estimated from height models, derived from photogrammetry data**: This graph shows the relation between the perpendicular tree height and the estimated tree height - once in summer and once in winter - for each species separately. Additionally a regression line was added in the lower panel, while the correlation value appears in the upper panel.

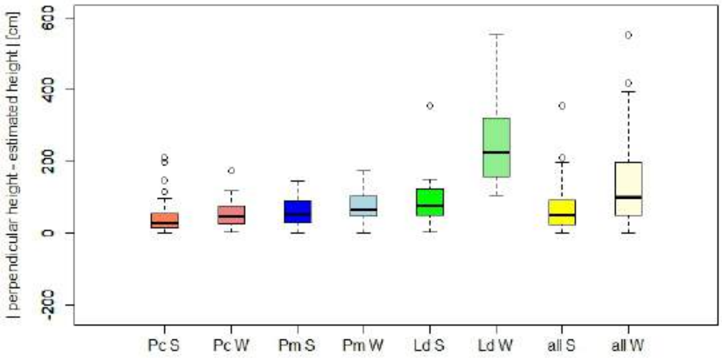


**Figure 3.6: Difference between tree heights in summer 2015 and winter 2016- assessed manually or estimated from height models, derived from photogrammetry data**: This graph shows the relation between the absolute difference between the perpendicular tree heights and the estimated tree heights for each species (Pc = *Pinus cembra* (red), Pm = *Pinus mugo* (blue), Ld = *Larix decidua* (green)) separately and all assessed trees together(all, (yellow)). The heights were assessed in summer 2015 (S) and winter 2016 (W).

**(a)** *Pinus cembra*, winter 2016 **(b)** *Pinus cembra*, summer 2015

**(c)** *Pinus mugo*, winter 2016 **(d)** *Pinus mugo*, summer 2015

**(e)** *Larix decidua*, winter 2016 **(f)** *Larix decidua*, summer 2015

**Figure 3.7: Distribution of the measurement error for each species in each season**: This graph shows the frequency of the measurement error (manually - estimated) for each species separate in summer 2015 and winter 2016. The mean is indicated by the red line and zero by the blue line.

## 3.4 Snow depth - manually assessed vs estimated

The manually assessed snow depth was greater than the ones estimated from height models, derived from photogrammetry data (median manually = 107 cm, estimated = 88 cm)(figure 3.8). Furthermore, the variance of the estimated snow depth was greater. The Pearson's r of these two variables is 0.66 (p-value = 0.0133)(figure 3.9). The RMSE is 35.20 cm.

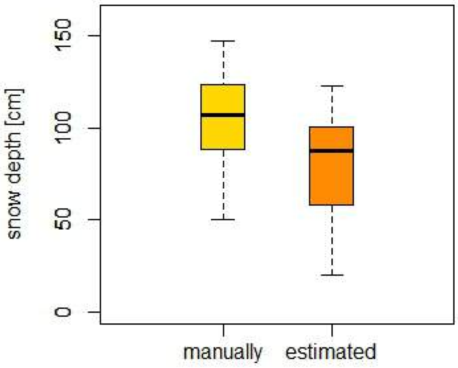


**Figure 3.8: Snow depth in forest gaps - assessed manually or estimated from height models, derived from photogrammetry data**: This graphic shows the snow depth assessed with 2 different methods. The snow depth was measured manually (yellow bar) and estimated (orange) from model 1 (table 2.2).

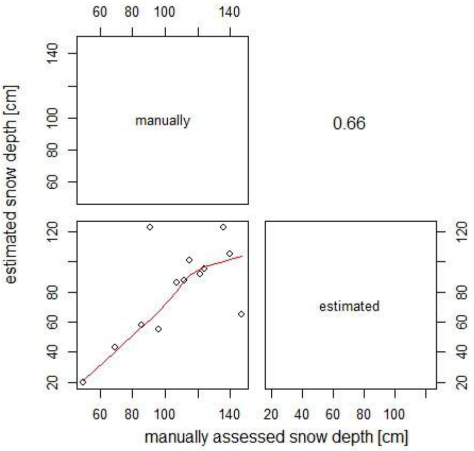


**Figure 3.9: Relation between the snow depth in forest gaps - assessed manually or estimated from height models, derived from photogrammetry data**: This graph shows the relationship of the manually assessed snow depth and the estimated snow depth from model 1 (table 2.2). Additionally a regression line was added in the lower panel, while the Pearson's r appears in the upper panel.

The differences between the snow depth measurements in the single locations can be seen in figure 3.10. The estimated value underestimated the snow depth compared to the manually assessed one, with one exception on measurement location number 15. For the measurement location 1 and 6 the estimated snow depth is missing, since these spots have been outside the UAS flight area.

The distribution of the measurement error showed, that the estimated snow depth underestimated the real snow depth by 26 cm (mean error)(figure 3.11).
In this section, only the height model, which suited the manually assessed snow depth best, was introduced to the reader. Further results of additional height models can be found in the Appendix A.

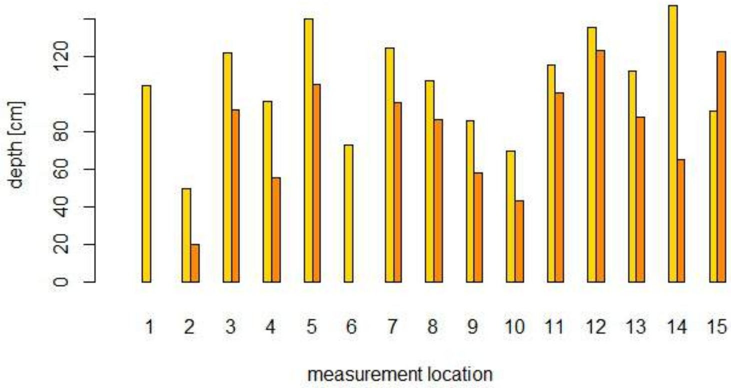


**Figure 3.10: Differences between the snow depth - assessed manually or estimated from height models, derived from photogrammetry data**: The bars show the snow depth assessed with two different methods. It was measured manually (yellow bar) and estimated from model 1 (orange) (table 2.2).

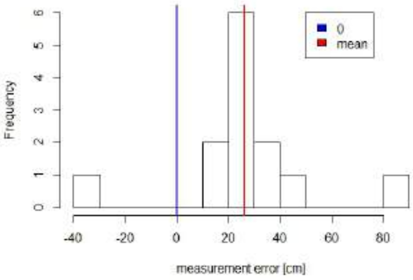


**Figure 3.11: Distribution of the measurement error for the snow depth in forest gaps**: The bars show the frequency of the measurement error in snow depth. The mean of the error (red) is 26 cm.

# 4

# Discussion

## 4.1 Limitations resulting from measurement design

The localisation of the individual trees in the field was difficult because in winter the cable of the small funicular, avalanche barriers and the trees themselves were the only orientation points. In summer small metal stakes marked the upper left corner of the unit area, which helped to adjust the position and orientation. Today only 3% of *Pinus cembra*, 7% of *Pinus mugo* and 58% of *Larix decidua* are alive (Blatter, 2016). Therefore, the individuals of *Pinus cembra* were the easiest ones to localise. For *Larix decidua* the major problem was to identify the correct individual since most of the individuals survived. *Pinus mugo* was most difficult to localise because the individuals were partly or totally covered with snow. Consequently, the selection of the individuals was not random since only the trees, which were partly uncovered, were found and assessed. The totally covered trees could not be assessed due to the following two problems. If the tree was totally covered, it could not be localised. Secondly, the position of the tip changes, as the tree is bent due to the snow cover. Assuming one could determine the position of the tree, the assessment of the height of the tree tip would still complicated. If one starts to dig out the tree, the amount of snow pressing it down would change and therefore the position of the tip would be altered as well. The individuals of *Pinus mugo*, assessed in this thesis, furthermore, showed two different ways of interacting with the snow cover. In the first case a part of the tree was sticking out of the continuous snow cover. In a few cases the tree was bent due to the snow, but formed a snow-free shelter on the downhill side of the stem, containing only a small snow depth or even a snow-free spot perpendicular underneath the tip (figure 4.1).

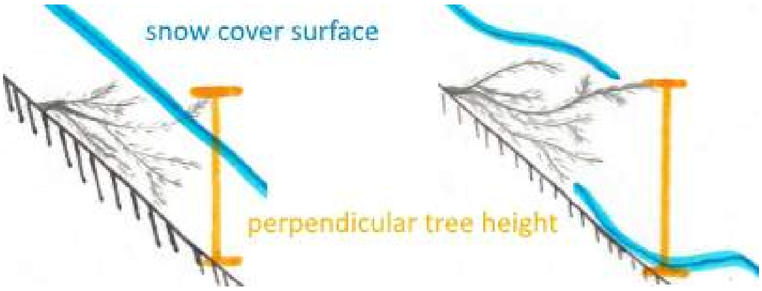


**Figure 4.1: Sketch of the two alternatives how *Pinus mugo* interacted with the snow cover**

## 4.2 Snow depth perpendicular underneath the tree tip - depending on the tree species

The snow depth perpendicular underneath the tree tip was the largest for *Larix decidua* and the smallest for *Pinus cembra*. This result can be explained by the interception. The surface area of the branches of the evergreen *Pinus cembra* is much larger than the one of the deciduous *Larix decidua* leading to the ability of evergreen species to intercept a larger amount of snow(Frey, 1977; Hedstrom and Pomeroy, 1998). While the snow is partly retained by the branches of *Pinus cembra*, only little is retained by the branches of *Larix decidua*. The snow remaining on the branches will either fall through the branches to the ground later on, be redistributed by wind or sublimate directly from the branches (Margreth, 2004; Schneebeli and Bebi, 2004). The low snow depth underneath *Pinus cembra* is further explainable by the fact, that it mainly survived at sun facing ridges with eastern exposition with low snow depth (Bebi et al., 2009). Moreover, a snow-free area is often built around the stem. This is likely to result from the effects of interception and snow redistribution. Additionally this can be influenced by the radiation budget. The darker bark and crown of the evergreen species have a lower albedo than the deciduous *Larix decidua* with a bright bark. Margreth (2004) states, that the micro-climate underneath a evergreen forest is more balanced than over the open field. Though it is stated for a forest, small groups of *Pinus cembra* are likely to show a similar effect. Therefore, an additional hypothesis could be a change in the micro-climate by evergreen species, creating a warmer micro-climate, leading to snow melting. The effect of snow redistribution by near-surface wind which fills up subsequent openings might be important (Schneebeli and Bebi, 2004; Margreth, 2004).

The snow depth underneath *Pinus mugo* is neither as shallow as the one for *Pinus cembra*, nor as deep as for *Larix decidua*. Although it is evergreen and could therefore have a large influence on the interception of the falling snow, this effect is not dominating. Which can be explained by the fact that most of the individuals have been partly or even totally covered with snow. The resulting problems in the field investigation are described in the subsection 4.1.

The results showed a clear dependency of the amount of snow accumulating underneath the tree tip on the tree species. It was smaller for the two evergreen species (*Pinus cembra, Pinus mugo*) than for the deciduous species (*Larix decidua*).

## 4.3 Snow depth perpendicular underneath the tree tip - depending on the tree length

Snow depth decreased with increasing tree length for all investigated species. Generally, the crown area of a tree increases with the diameter at breast height (DBH) and age (Zhu et al., 2015). The result of *Pinus cembra* can therefore be explained by increasing influence on the falling snow due to increased interception via a larger surface. At the same time the results showed that the snow-free spots underneath the trees were distributed over all assessed heights. This could be due to factors such as relative position of the individual to the surrounding trees, exposition or small scale terrain type (depression, bump). All of these factors have a large influence on solar radiation and wind. Which indirectly results in snow melting or redistribution. However, the factor wind can also contribute to the transport of snow to sites which would be snow-free due to the snow interception and solar radiation. This in turn depends on the position of the location within the stand since various studies show that snow redistribution within forest stands are not the most important processes (Gubler and Rychetnik, 1991; Margreth, 2004).

Similar to *Pinus cembra*, *Larix decidua* showed a decrease of snow depth perpendicular underneath the tree tip with increasing height. This could be due to the growing number of branches with increasing height preventing the snow from falling directly to the ground. If the tree is positioned at a location where snow distribution by wind is relevant, the number of branches reaching down into the snow cover may also minimise the transportation of additional snow by wind, if they form a shelter-like structure around the stem.

The values of *Pinus mugo* resulted in a point cloud with no significant correlation. This can be explained by the influence of the snow depth on the shape and position of the individuals. All assessed *Pinus mugo* individuals have been more or less strongly bent by the snow cover. To be able to assess the interaction of *Pinus mugo* and the snow cover, the experimental design needs to be adapted (see section 4.2).

## 4.4 Tree height - a comparison of two different methods

The accordance of the two methods was depending on the tree species and the season. Showing a better result in summer than in winter for all species, with one exception. Generally, the difference between the two methods includes various small error sources:

- accuracy of the DEMs
- geographical accordance of the DEMs
- closeness of the tree tip position in ArcGIS
- measurement error in the field data

**Accuracy of the DEMs** The accuracy of the DEMs depends on different factors. Fisher and Tate (2006) distinguish three different categories of error sources: A) data acquisition method, B) processing and interpolation of the data, C) surface characteristics. Bühler et al. (2012) showed, that the accuracy of the DSM decreases with weak illumination and steepness of the slope. Additionally, it depends on different variables during the UAS flight mission such as wind, age and structure of the snow cover surface and exposure of the camera (Bühler et al., 2016). The accuracy of the DTM depends on terrain, vegetation and flight planning. The terrain leads to positional errors due uncertainties in planimetric position of the assessed elevation and spreading of the laser spot on the ground. The strength of the return signal is strongly influenced by the canopy density of the vegetation. Flight planing can reduce the terrain shadowing and gaps in laser return (Deems et al., 2013). The DSM records the upper most value, large enough to be recognized which may be the ring of needles, while the manually assessed tree height aims to exclude them. This difference however is in the same range as the height accuracy of the DEMs.

**Geographical accordance of the DEMs** The geographical accordance of the models depends on the accuracy of the ground control points, used to absolutely orientate the models geographically. The accuracy of the ground control points was better than 10 cm. The accuracy of the geographical position determines the accuracy of the resulting HM and therefore the accuracy of the values extracted from the HM.

**Closeness of the tree tip position in ArcGIS** The tree height estimated from the HM was extracted from points which were manually created in ArcGIS, according to the best visible accordance of tree position in the orthophoto and the tree structure visible in the HM. While the position of the tree was often easily allocable in the orthophoto, it was much more difficult to determine the exact position of the tree tip. The position of the individual was easily allocable in the winter orthophoto (RGB), whereas it was more difficult in the summer orthophoto (NIR), especially for *Pinus mugo*. One problem was, that a few of the assessed *Pinus mugo* were partly covered by *Larix decidua* branches, which in summer form a more or less dense canopy, while in winter the branches are bald. It may be possible that in this cases the estimated tree height did not represent the tip of *Pinus mugo* but a branch of *Larix decidua*. For *Larix decidua* the allocation of the tree tip in the winter orthophoto was more difficult than in summer. This is due to the size of the tree tip which is smaller than the resolution of the winter DSM (5 cm). Shadows and branches made it even more difficult. In summer, the tree tip is larger, due to the needles, making the allocation of the tree tip in the summer orthophoto much easier. The allocation of *Pinus cembra* was possible with the data of both seasons. The localisation of the tree tip though was difficult, since the habitus of *Pinus cembra* is not always cone-shaped but can also be pillar-shaped (Rickli, 1909).

**Measurement error in the field data** The error for the manually assessed tree height increased with height. For *Larix decidua* the tree tip was clearly recognizable, while for *Pinus cembra* it was more difficult because of the needles forming a ring around the tree tip. But the more important problem is, that the larger the tree is, the further away the observer needs to be, to determine whether the yard stick is on the same position as the tree tip. Sometimes the distance to the tree can not be as large as desired, because another object would be between the tree tip and the observer. Furthermore, different observers have a different estimation, leading to small discrepancies.

Despite all of these error sources, the results showed a clear relation of the values gained from the two methods: The manually assessed tree heights were larger than the estimated ones for all species in both season, with one exception. The tree heights of the two different methods corresponded best for *Pinus cembra* in summer and in winter. While the manually assessed tree height was larger than the estimated one in winter, it was vice versa in summer. The distribution of the measurement errors show that the tree height was underestimated by 48 cm in winter, whereas in summer it was overestimated by 4 cm. However, the latter value was in the same range as height accuracy of the model. Considering the difficulties of assessing variables for *Pinus mugo* one would expect that the values from the two different methods would show a low relation in winter. The tree heights were less underestimated in summer (mean error = 42 cm) than in winter (64 cm).
While the season did not have a large impact on the difference between the two methods for the evergreen species it did for *Larix decidua*. The error distribution showed that the mean error in winter was almost twice as large as for the evergreen species and was more than twice as large in winter than in summer. First of all the tree tip of *Larix decidua* was smaller in both seasons compared to the other two species, which made it even more difficult to assess its tree height with UAS-based photogrammetry data. Not only was the allocation of the tree tip in the winter orthophoto difficult because of its size, shadows and branches, but furthermore, the size of the tip was smaller than the resolution of the winter DSM (5 cm). In summer, the tree tip is larger due to the needles. Also the allocation of the tree tip in the summer orthophoto was much easier. This was visible in the data, showing that the difference between the two methods was more than four times larger in winter compared to summer. The correlation of the tree heights assessed with the two methods in summer was even better than for *Pinus cembra* in either of the seasons.

In winter, the match of the two methods was much better for the evergreen species than for deciduous *Larix decidua*. For all the three species the match of the two methods was better in summer than in winter, though it did not matter so much for *Pinus cembra* and *Pinus mugo*. For *Larix decidua* however, the match was much better in summer than in winter.

## 4.5 Snow depth in forest gaps - a comparison of two different methods

The results of the snow depth measurements in forest gaps showed, that the snow depth values gained from the HM (model 1) underestimated the snow depth by 26 cm compared to the value gained with manual avalanche probe measurements, with one exception. This is in line with the findings of Bühler et al. (2015a).

This statement contains not negligible assumptions. **Assumption 1**: The manually assessed snow depth equals the real snow depth. This variable in turn is strongly influenced by the understorey vegetation in the site. At the research area Stillberg the alpine rose (*Rhododendron ferrugineum*), different species of the genus *Vaccinieae*, different grasses and tall forbs determine the understorey vegetation. The snow cover presses it to the ground surface, where it builds up a layer of a few centimetres. When measuring the snow depth, the avalanche probe may penetrate this vegetation cover, which will lead to a snow depth value, which contains the real snow depth and the thickness of the vegetation cover (Bühler et al., 2016). **Assumption 2**: The calculated HM mirrors the real snow depth. This is based on further assumptions: The DSM reflects the height position of the surface most accurately. The DTM precisely represents the small-scale variation of the topography of the bare ground and contains no errors such as accepting a dense vegetation cover as ground surface. Furthermore, the geographical position of the two models is assumed to be exact to enable the subtraction without loss in accuracy. Moreover, the resolution of the resulting HM is important. The HM had a resolution of 20 cm and the snow depth measurements were taken in a square of approximately one metre side length. Depending on the small scale variation of the topography the mean of the five manually measured snow depth values may not represent the average snow depth in this square. Furthermore, the snow depth value gained from the HM was only taken from the measurement point in the middle of the square and is therefore not the average of all five measurement points.

The measurement location number 15 was the exception in which the estimated snow depth was larger than the manually assessed one. This can not be explained by the available information for the test site. In a larger sample size this case will either be more common or insignificant in its number of appearance.

# 5

# Conclusion

The results clearly showed the influence of the trees on the snow depth in their crown area. It demonstrated that the snow depth was as much as 10 times smaller underneath the evergreen *Pinus cembra* compared to the deciduous *Larix decidua.* The snow depth underneath *Pinus mugo* resided between the values for the other two species. No general conclusion was possible for the influence of *Pinus mugo* on the snow depth since the experimental design of this thesis only assessed trees visible in winter.

Furthermore, the snow cover was influenced by the length of the tree, although the relation was weak for all three species. Future research should consider to assess the influence of the number of branches on the snow depth in the crown area.

To be able to assess the interaction of *Pinus mugo* and the snow cover the experimental design needs to be adapted. The position of the individuals should be marked in autumn before the first snow falls. It could be important to assess variables such as height, length of the trunk and branches, canopy area, degree of bending with increasing snow load, exposition and steepness of the test site to be able to draw a conclusion on how the species interacts with the snow cover.

The potential of newly available remote sensing techniques to assess tree heights and snow depth was demonstrated by the results of this thesis. Whereas the tree height assessment for evergreen species showed similar results independent of the season in which the data acquisition took place, it was crucial for *Larix decidua* to perform the assessment in summer. Future studies could focus on the evaluation of a factor correcting the difference between the estimated value from the HM and the manually assessed value.

The snow depth, estimated from height models, derived from photogrammetry data, were constantly lower than the manually assessed ones - with one exception. However, the sample size in this thesis was to small. Future experiments should consider to enlarge the sample size and include further variables influencing the snow depth and the accuracy of the DSM to be able to explain the difference between the methods accurately. The variables may be: wind (at the snow cover surface over a longer time period to be able to include the influence on snow distribution, as well as during the UAS flight, influencing the DSM accuracy), understorey vegetation, exposition and steepness of the site. With a larger sample size it may be possible to evaluate a correction factor depending on the surface structure.

# Bibliography

[1] Barbeito, I., Dawes, M. A., Rixen, C., Senn, J., Bebi, P., 2012. Factors driving mortality and growth at treeline: a 30-year experiment of 92000 conifers. Ecology 93, 389–401.

[2] Bebi, P., Hagedorn, F., Martin, M., Rixen, C., Senn, J., Wasem, U., 2009. Langfristige Waldgrenzen-Forschung am Stillberg – vor lauter Bäumen den Wald noch sehen. Forum für Wissen, 87–92.

[3] Blatter, S., 2016. Growth of treeline trees. A spatial-temporal analysis of driving forces on tree growth at treeline. ETH Zürich, Master thesis.

[4] Bühler, Y., Adams, M.S., Bösch, R., Stoffel, A., 2016. Mapping snow depth in alpine terrain with unmanned aerial systems (UASs): potential and limitations. The Cryosphere 10, 1075–1088. doi:10.5194/tc-10-1075-2016

[5] Bühler, Y., Marty, M., Egli, L., Veitinger, J., Jonas, T., Thee, P., Ginzler, C., 2015b. Snow depth mapping in high-alpine catchments using digital photogrammetry. The Cryosphere 9, 229–243. doi:10.5194/tc-9-229-2015

[6] Bühler, Y., Marty, M., Ginzler, C., 2012. High Resolution DEM Generation in High-Alpine Terrain Using Airborne Remote Sensing Techniques: High Resolution DEM Generation in High-Alpine Terrain. Transactions in GIS 16, 635–647. doi:10.1111/j.1467-9671.2012.01331.x

[7] Bühler, Y., Bösch, R., Stoffel, A., Adams, M., 2015a. Geodatenerfassung im hochalpinen Gelände mittels Drohnen. Géomatique Suisse, 366-370.

[8] Deems, J.S., Painter, T.H., Finnegan, D.C., 2013. Lidar measurement of snow depth: a review. Journal of Glaciology 59, 467–479. doi:10.3189/2013JoG12J154

[9] Ellenberg, H., Klötzli, F., 1972. Waldgesellschaften und Waldstandorte der Schweiz. Mitt. Eidgenöss. Forsch.anst. Wald Schnee Landsch. 48, 587–930.

[10] ESRI, 2015. ArcGIS for Desktop. ArcMap 10.3 Environmental Systems Research Institute. URL http://www.arcgis.com/.

[11] Fisher, P., Tate, N., 2006. Causes and consequences of error in digital elevation models. Progress in Physical Geography, 467–489.

[12] Frey, W., 1977. Wechselseitige Beziehung zwichen Schnee und Pflanze- eine Zusammenstellung anhand von Literatur, Nr. 34.

[13] Grace, J., Berninger, F., Nagy, L., 2002. Impacts of Climate Change on the Tree Line. Annals of Botany 90, 537–544. doi:10.1093/aob/mcf222

[14] Gubler, H., Rychetnik, J., 1991. Effects of forests near the timberline on avalanche formation. IAHS 205, 19–38.

[15] Hedstrom, N.R., Pomeroy, J.W., 1998. Measurements and modelling of snow interception in the boreal forest. Hydrol. Process., 1611–1625.

[16] Hlásny, T., Křístek, Š., Holuša, J., Trombik, J., Urbaňcová, N., 2011. Snow disturbances in secondary Norway spruce forests in Central Europe: Regression modeling and its implications for forest management. Forest Ecology and Management 262, 2151–2161. doi:10.1016/j.foreco.2011.08.005

[17] Höhle, J., Höhle, M., 2009. Accuracy assessment of digital elevation models by means of robust statistical methods. ISPRS Journal of Photogrammetry and Remote Sensing 64, 398–406. doi:10.1016/j.isprsjprs.2009.02.003

[18] Holtmeier, F.-K., 2009. Mountain Timberlines, 2nd ed. Springer, Dordrecht.

[19] Kellomäki, S., Peltola, H., 1999. Silvicultural strategies in forest management to optimise yield and growth in boreal forests while minimising the risks of wind and snow damage. Transactions on Ecology and the Environment 27, 285–303.

[20] López-Moreno, J.I., Latron, J., 2008. Influence of canopy density on snow distribution in a temperate mountain range. Hydrological Processes 22, 117–126. doi:10.1002/hyp.6572

[21] López-Moreno, J.I., Stähli, M., 2008. Statistical analysis of the snow cover variability in a subalpine watershed: Assessing the role of topography and forest interactions. Journal of Hydrology 348, 379–394. doi:10.1016/j.jhydrol.2007.10.018

[22] Margreth, S., 2004. Die Wirkung des Waldes bei Lawinen. Forum für Wissen, 21–26.

[23] Marty, M., 2016. Abschlussbericht Stillberg Sommer 2015. SLF, internal report, 12-15.

[24] Meyer- Grass, M., Schneebeli, M., 1992. Die Abhängigkeit der Waldlawinen von Standorts-, Bestandes-, und Schneeverhältnissen. Internationales Symposium INTERPRAEVENT 1992- Bern, Tagespublikation 2, 443–455.

[25] Nykänen, M.-L., Peltola, H., Quine, C.P., Kellomäki, S., Broadgate, M., 1997. Factors Affecting Snow Damage of Trees with Particular Reference to European Conditions. Silva Fennica 31, 193–213.

[26] Rasmus, S., Lundell, R., Saarinen, T., 2011. Interactions between snow, canopy, and vegetation in a boreal coniferous forest. Plant Ecology & Diversity 4, 55–65. doi:10.1080/17550874.2011.558126

[27] Revuelto, J., López-Moreno, J.I., Azorin-Molina, C., Vicente-Serrano, S.M., 2015. Canopy influence on snow depth distribution in a pine stand determined from terrestrial laser data: Canopy influence on snow depth distribution. Water Resources Research 51, 3476–3489. doi:10.1002/2014WR016496

[28] R Core Team (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

[29] Rickli, M., 1909. Die Arve der Schweiz. Ein Beitrag zur Waldgeschichte und Waldwirktschaft der Schweizer Alpen. Kommissions-Verlag von Georg & Cie., Zürich.

[30] Salm, B., 1978. Snow forces on forest plants. In: Proceedings IUFRO Seminar Mountain Forests and Avalanches, Davos, Switzerland, 157–182.

[31] Schirmer, M., Wirz, V., Clifton, A., Lehning, M., 2011. Persistence in intra-annual snow depth distribution: 1. Measurements and topographic control:

PERSISTENT SNOW DEPTH DEVELOPMENT, 1. Water Resources Research 47, W09516, doi:10.1029/2010WR009426

[32] Schneebeli, M., Bebi, P., 2004. Snow and avalanche control, in: Youngquist, J.A. (Ed.), Encyclopedia of Forest Sciences. Elsevier, 397–402.

[33] Senn, J., Schönenberger, W., n.d. Zwanzig Jahre Versuchsaufforstung Stillberg: Überleben und Wachstum einer subalpinen Aufforstung in Abhängigkeit vom Standort. Schweiz. Z. Forstwes. 152, 226–246.

[34] Subedi, M.R., 2009. Climate change and its potential effects on tree line position: an introduction and analysis. The Greenery- A journal of Environment and Biodiversity 7, 17–21.

[35] Wieser, G., 2012. Lessons from the timberline ecotone in the Central Tyrolean Alps: a review. Plant Ecology & Diversity 5, 127–139. doi:10.1080/17550874.2010.498062

[36] Wieser, G., Tausz, M. (Eds.), 2007. Trees at their upper limit: treelife limitation at the Alpine timberline, Plant ecophysiology. Springer, Dordrecht.

[37] Zhu, L., Zhou, T., Chen, B., Peng, S., 2015. How does tree age influence damage and recovery in forests impacted by freezing rain and snow? Science China Life Sciences 58, 472–479. doi:10.1007/s11427-014-4722-2

[38] Zhu, J.-j., Li, X., Liu, Z., Cao, W., Gonda, Y., Matsuzaki, T., 2006. Factors Affecting the Snow and wind Induced damage of a montane secondary forest in Northeastern China. Silva Fennica 40, 37–51.

# A

# Appendix A

The median, correlation value, as well as its p-value can be withdrawn from table A.1.

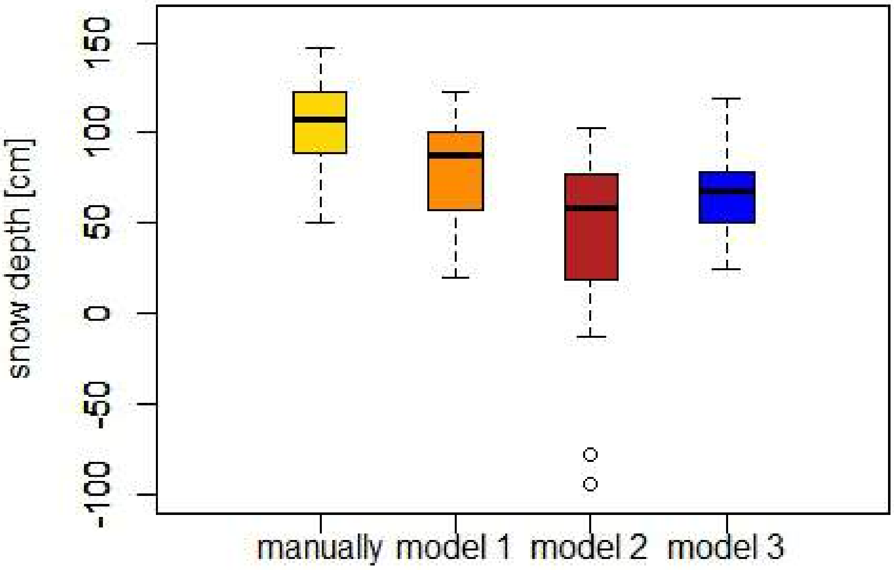


**Figure A.1: Snow depth in forest gaps - assessed with two different methods**: This graphic shows the box plots of the snow depth assessed with 2 different methods. The snow depth was measured manually (yellow bar). Furthermore, the snow depth was estimated from 3 different models: Model 1 is the difference of the DSM of the 11-04-2016 and the DTM of the ALS data (orange). Model 2 is the difference of the DSM of 11-04-2016 and the DSM of the 12-08-2015 (red). Model 3 is the difference from the DSM of the 11-04-2016 and the DTM from the UAS data of the 12-08-2015 (blue). (detailed information about the used models can be extracted from table 2.1 and table 2.2 .)

**Table A.1:** Median and Pearson correlation values of the snow depth- assessed manually or estimated from height models, derived from photogrammetry

| Method | Median [cm] | Correlation value of manually and from models estimated snow depths | P-value |
|---|---|---|---|
| manually assessed | 107 | - | - |
| model 1 | 88 | 0.66 | 0.0133 |
| model 2 | 59 | 0.66 | 0.5203 |
| model 3 | 68 | 0.66 | 0.3257 |

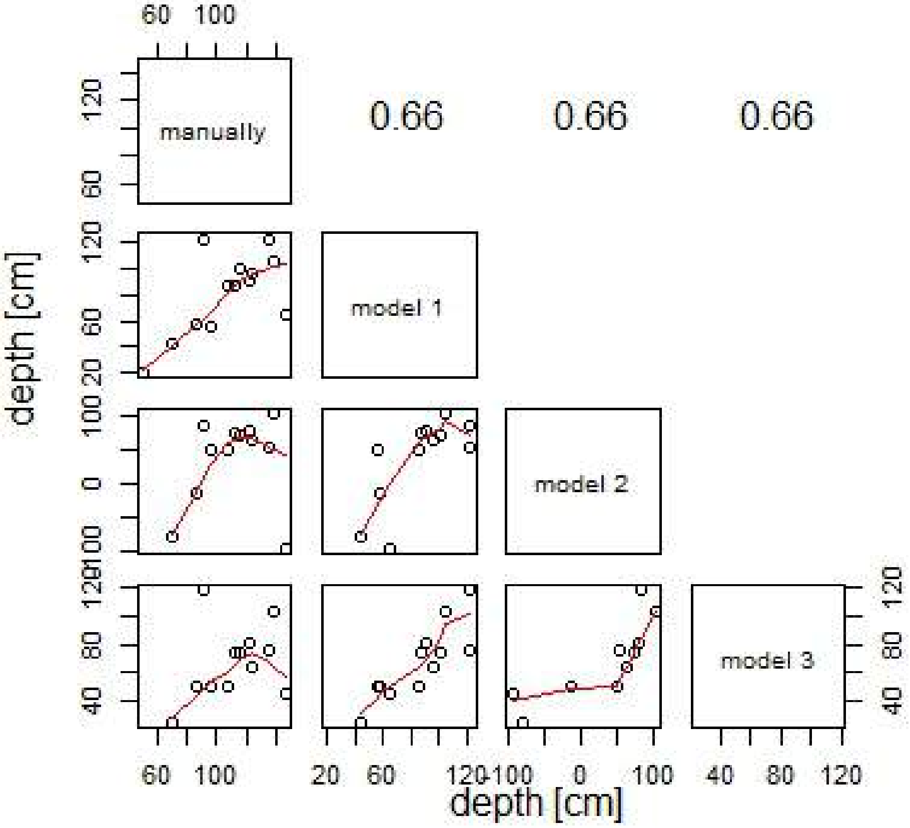


**Figure A.2: Scatter plots of the snow depth - assessed with different methods**: This graphic shows the snow depth- manually assessed and estimated from three different models. It compares the following four variables with one another: the manually measured snow depth, the estimated snow depth of three different models. Model 1 is the difference of the DSM of the 11-04-2016 and the DTM of the ALS data (orange). Model 2 is the difference of the DSM of 11-04-2016 and the DSM of the 12-08-2015 (red). Model 3 is the difference from the DSM of the 11-04-2016 and the DTM from the UAS data of the 12-08-2015 (blue). (for detailed information see table 2.1.) Additionally a regression line was added in the lower panels, while the correlation value of the manually assessed snow depth and one of the models appears in the upper panel. The depths are indicated in cm. (detailed information about the used models can be extracted from table 2.1 and table 2.2.)

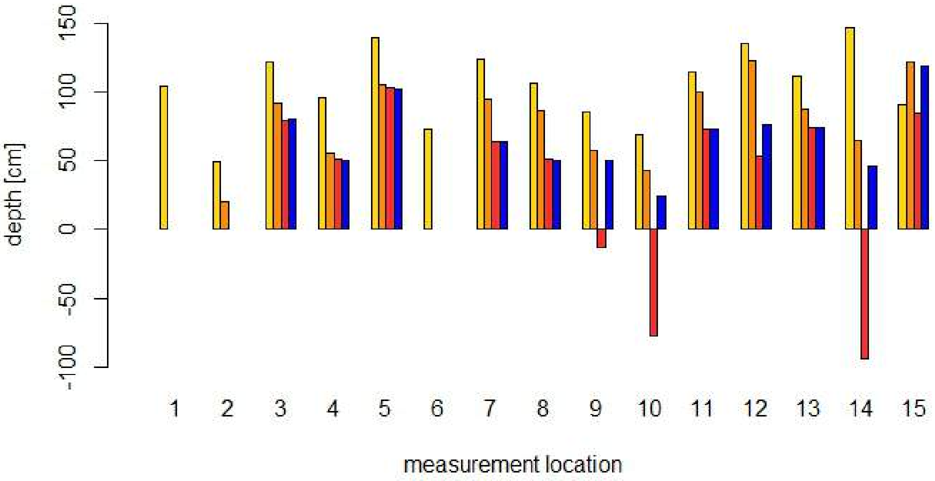


**Figure A.3: Differences between snow depth in forest gaps - assessed with two different methods**: The bars show the snow depth assessed with two different methods. It was measured manually (yellow) and estimated from different three different models: Model 1 is the difference of the DSM of the 11-04-2016 and the DTM of the ALS Data (orange). Model 2 is the difference of the DSM from 11-04-2016 and the DSM of the 12-08-2015 (red). Model 3 is the difference from the DSM of the 11-04-2016 and the DTM from the UAS data of the 12-08-2015 (blue). Detailed information about the used models can be extracted from table 2.1 and table 2.2. The snow depths are indicated in cm. The correlation of the manually assessed snow depth with each model is 0.66 (p-value for model 1 = 0.013, for model 2 = 0.520, for model 3 = 0.326)

# B

# Appendix B

**ETH**

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

## Eigenständigkeitserklärung

Die unterzeichnete Eigenständigkeitserklärung ist Bestandteil jeder während des Studiums verfassten Semester-, Bachelor- und Master-Arbeit oder anderen Abschlussarbeit (auch der jeweils elektronischen Version).

Die Dozentinnen und Dozenten können auch für andere bei ihnen verfasste schriftliche Arbeiten eine Eigenständigkeitserklärung verlangen.

---

Ich bestätige, die vorliegende Arbeit selbständig und in eigenen Worten verfasst zu haben. Davon ausgenommen sind sprachliche und inhaltliche Korrekturvorschläge durch die Betreuer und Betreuerinnen der Arbeit.

**Titel der Arbeit** (in Druckschrift):

Interaction of trees and snow cover in the treeline ecotone

**Verfasst von** (in Druckschrift):

*Bei Gruppenarbeiten sind die Namen aller Verfasserinnen und Verfasser erforderlich.*

| **Name(n):** | **Vorname(n):** |
|---|---|
| Isler | Julia Luzia |

Ich bestätige mit meiner Unterschrift:

- Ich habe keine im Merkblatt „Zitier-Knigge" beschriebene Form des Plagiats begangen.
- Ich habe alle Methoden, Daten und Arbeitsabläufe wahrheitsgetreu dokumentiert.
- Ich habe keine Daten manipuliert.
- Ich habe alle Personen erwähnt, welche die Arbeit wesentlich unterstützt haben.

Ich nehme zur Kenntnis, dass die Arbeit mit elektronischen Hilfsmitteln auf Plagiate überprüft werden kann.

| **Ort, Datum** | **Unterschrift(en)** |
|---|---|
| Davos, 8. Juli 2016 | |

*Bei Gruppenarbeiten sind die Namen aller Verfasserinnen und Verfasser erforderlich. Durch die Unterschriften bürgen sie gemeinsam für den gesamten Inhalt dieser schriftlichen Arbeit.*